An optimized design of in-shoe heel lifts reduces plantar pressure of healthy males

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Abstract:

Conventional heel lift with a flat surface increases the risk of foot problems related to higher plantar pressure and decreased stability. In this study, an optimized design of in-shoe heel lifts developed to maintain the midfoot function was tested to investigate if the plantar pressure distribution was improved. The design was based on three dimensional foot plantar contour which was captured by an Infoot 3D scanning system while the heel was elevated by a heel wedge. To facilitate midfoot function, an arch support was designed to support the lateral longitudinal arch, while allowing functional movement of the medial longitudinal arch. Twenty healthy male subjects were asked to walk along an 8 m walkway while wearing high-cut footwear with and without the optimized heel lift. Peak pressure, contact area and force-time integral were measured using the Pedar insole system. Range and velocity of medial-lateral center of pressure during forefoot contact phase and foot flat phase were collected using a Footscan pressure plate. Compared to the shoe only condition, peak pressure under the rearfoot decreased with the optimized heel lift, while no increase of peak pressure was observed under the forefoot and midfoot regions, indicating improved plantar pressure distribution. The findings of this study suggest that this optimized heel lift has better biomechanical performance than a conventional flat heel lift. Results from this study may have implications for insole and shoe last design, especially for people who need additional heel height without sacrificing midfoot function.

Keywords: Heel lift; Arch support; Plantar pressure; Center of pressure.

1. Introduction

In-shoe heel lift is adopted as a leg length adjustment device for leg length discrepancy [1], and is also recommended for the treatment of some lower extremity problems which are associated with overload in Achilles tendon and high peak pressure under the rearfoot [2, 3] (the terms “heel” and “rearfoot” are used interchangeably throughout the paper). However, it was suggested that heel lifts should be used with caution, because of an increase in peak pressure and pressure-time integral under the forefoot [4, 5]. High peak pressure is a risk factor for foot problems, as it may cause discomfort and is associated with some foot pathologies, e. g. diabetic foot ulcers [6]. Our previous study on flat heel lift also showed an increase in range and velocity of medial-lateral center of pressure (COP) during walking [5]. This increased movement of COP in medial-lateral direction indicates greater demand of stability control. Most of the tested heel lifts were heel wedges without contoured surface and arch support, which provide insufficient support to the elevated midfoot.

The foot rolls from heel to toe during walking. Each part of the foot is related to a different functional demand, with the heel mainly related to aspects such as absorbing impact, transferring load to the leg and the forefoot mainly related to propulsion. Numerous studies have focused on rearfoot motion control [7, 8] and forefoot load relief [6], while the midfoot as a linkage between the forefoot and rearfoot, has drawn far less attention.

The midfoot consists of a medial and a lateral longitudinal arch. The medial longitudinal arch of the human foot acts as a spring during locomotion which allows mechanical energy to be stored and recoiled to benefit gait efficiency [9]. Restraining arch movement would affect the windlass mechanism and lead to a possible decrease in the efficiency of sagittal plane motion. According to the sagittal plane facilitation theory, when there is a sagittal plane block or deficiency, the foot and ankle complex must compensate somewhere along the kinetic chain [10]. Moreover, the studies conducted by Wegener et al. showed that the midfoot joint plays an important role in energy production during the propulsion phase of both walking and running [11]. Interfering with the medial longitudinal arch function might have an impact on gait efficiency and increase risk for lower limb injuries. The lateral longitudinal arch is always in contact with the ground during locomotion in normal foot type, which is important to stabilize the heel-to-toe movement. With the heel elevated, however, both medial and lateral longitudinal arches are suspended, presenting a situation similar to a high arch foot. The midfoot has an important role in weight bearing and transferring load from the rearfoot to forefoot. Thus we assumed that the higher plantar pressure and decreased stability caused by flat heel lifts may be associated with the lack of support to the midfoot.

In order to improve the midfoot function when using heel lifts, a new design of arch support was developed and tested in this study. Arch support has been widely adopted as a type of insoles to enhance biomechanical performance, such as redistributing plantar pressure, relieving load on plantar fascia and decreasing knee adduction moment [12-16]. Arch support is also used in motion control shoes to improve foot balance by supporting the medial arch to control over-pronation [17]. Custom-made insoles with arch support and a contoured heel are used in foot care settings of diabetic patients [18]. As the contact area increases, load can be transferred from high load regions to adjacent areas [19]. Thus in order to distribute plantar pressure more evenly, the 'total contact' concept has been adopted to design insoles based on the plantar contour of the foot to provide full foot support. Total contact arch support has been shown to relieve load on plantar fascia effectively [12], however, these tests were conducted on cadavers, and thus its effects on foot dynamic function during locomotion is unknown. Previous studies suggested that the arch height varies between none weight bearing, standing and locomotion [20]. The "total contact" concept is valid to redistribute pressure over a rigid part, but if it is adopted for arch support design, it may induce a series of compensatory reactions by restraining the necessary motion of midfoot.

Therefore, we hypothesized that an optimized heel lift with a functional arch support that maintains the midfoot function may reduce the adverse effects of a flat heel lift, i.e. reducing peak pressure under forefoot and midfoot and reducing the range and velocity of the medial-lateral COP. Taking into account the characteristics of a heel lift and the shortcomings of the total contact insole, a new design of heel lift with a functional arch support is introduced. We hypothesized that the midfoot function would be preserved by fully supporting lateral longitudinal arch and allowing medial longitudinal arch the necessary range of motion, while also providing some support in case the foot over-pronated. This study is a sequel to our previous study on flat heel lift [5]. In order to make comparisons, the subject inclusion criteria, measurement protocol and the main researchers remained the same. Force-time integral, which is the integral of force with respect to the contact time, peak pressure and contact area were measured to study the plantar load distribution. The range and velocity of medial-lateral COP were recorded to assess stability. The purpose of this study was to determine the effect of the optimized heel lift on the plantar distribution and the stability control during walking. The results may provide implications for insole and shoe last design and could be beneficial for people needing leg length adjustment and heel pain relieve.

2. Methods

2.1. Subjects

Twenty healthy male adults gave informed consent and participated in this study. The average age of the subjects was 22.4 years (S.D. 0.9), average mass 57.5 kg (S.D. 9.5), average height 168.0 cm (S.D. 2.9). All participants had the same shoe size to avoid any effects of shoe size and for the convenience of center of pressure analyses. None of the subjects had a history of lower extremity injuries in the preceding year. All participants had normal arches, with the arch index (AI) was $0.21<AI<0.26$ [21]. The arch index was calculated by the Footscan analysis software (RSscan International, Belgium) according to the dynamic pressure data which was recorded by a Footscan pressure plate.

2.2. Materials and apparatus

High-cut flat canvas footwear was selected for our experiment. The Pedar® insole pressure measurement system (Novel GmbH, Munich, Germany) was used to record in-shoe plantar pressure at a frequency of 100 Hz. A 1 m Footscan® pressure plate (RSscan International, Belgium, with 8192 resistive sensors and a pixel resolution of 5.08mm x 7.62mm) was used to record COP coordinates at a measurement frequency of 250 Hz. Displacement of COP in medial-lateral direction was defined with respect to the x-axis, perpendicular to the longitudinal foot axis. This longitudinal foot axis was defined as the line from mid-heel to forefoot, between metatarsal head 2 and 3. Infoot 3D foot scanning system (I-Ware Laboratory Co., Ltd, Osaka, Japan) was used to capture foot dimensions.

2.3. Heel lifts design

Conventional arch support design is based on barefoot, while heel lifts put the foot in a more plantar-flexed position and deform the arch. Arch support designs based on the barefoot arch morphology may not be ideal to present the arch shape while using heel lifts. Therefore, foot dimensions were captured by 3D scanner with a heel lift under the heel. Based on the results of our previous study [5], the heel lift was optimized to be 1) 25 mm in height; 2) the length extended from the heel to the posterior side of the metatarsophalangeal joint; 3) the material was elastic with medium hardness (in this study, we used EVA with shore hardness of A 32); 4) it included an arch support and 5) it had a contoured heel.

The foot plantar contour was captured by the Infoot 3D foot scanning system while subjects were standing in a neutral position, with 25 mm flat heel lifts under both feet. The heel lift was modeled in the Delcam Powershape software, based on the foot dimension data. The arch support was designed to fully support lateral longitudinal arch by elevating the lateral part of heel lift to fully contact the lateral longitudinal arch. The medial arch support was designed not to contact with the contour of medial longitudinal arch in standing position, but also elevated in order to provide support in case the foot overpronated during locomotion. The designed model was used to manufacture the heel lift by an engraving machine.

2.4. Procedures

Test conditions were the shoe only condition and the shoe with the optimized heel lift condition. After a familiarization period of walking in each condition along the walkway for 5 minutes, participants were asked to walk along an 8-m walkway with an integrated 1-m RSscan footscan pressure plate, at their natural self-selected speed. Plantar pressure was recorded by Pedar insole pressure system. Five successful walking trials were recorded of each participant for each condition.

2.5. Data analysis

All analyses were performed for the right foot. The in-shoe data recorded by the Pedar system includes contact area, peak pressure and force-time integral. Perpendicular to the foot axis, the foot excluding the toes was divided in three equal lengths: forefoot area, midfoot area and heel area. The stance phase was divided into four phases: the initial contact phase, the forefoot contact phase, the foot flat phase and the forefoot push-off phase. Similar to our previous study, COP data during forefoot contact phase and foot flat phase were analysed because dynamic stability is maintained mainly in these phases [5]. Forefoot contact phase was the period from the first metatarsal contact until all metatarsal head areas made contact with the pressure plate. Foot flat phase followed forefoot contact phase and ended when the heel was off the ground. The range of the COP was calculated as the absolute difference between the largest and smallest x coordinate value of COP during the corresponding phase. Statistical analyses were performed using SPSS version 16.0 statistical analysis software. Paired samples t-tests were performed to analyze the effect of heel lift on the plantar pressure and COP variables. Significant differences between the variables of each condition were considered if $p < 0.05$.

3. Results

Comparison of contact area and peak pressure under forefoot, midfoot and rearfoot with and without the optimized heel lift are shown in figure 1 and figure 2, respectively. Compared to the shoe only condition, the optimized heel lift increased the contact area under the midfoot ($p < 0.001$). The optimized heel lift did not increase peak pressure under forefoot and midfoot regions. There was a reduction on peak pressure under the rearfoot with the optimized heel lift compared to the shoe only condition ($p < 0.001$).

Figure 3 illustrates percentage of force-time integral under five foot regions with and without the optimized heel lifts. Force-time integral under forefoot demonstrated a decrease with the optimized heel lift ($p = 0.006$), while force-time integral under toe area showed a increase($p = 0.001$). The force-time integral percentage under the midfoot was the same with and without the optimized heel lift.

The range and velocity of medial-lateral COP during forefoot contact phase and foot flat phase with and without the optimized heel lift are shown in figure 4 and figure 5, respectively. Compared to the shoe only condition, the medial-lateral COP velocity during forefoot contact phase increased with the use of the optimized heel lift, while no significant difference was found.

4 Discussion

Compared to the shoe only condition, the increase of the midfoot contact area with the optimized heel lift indicates good support for midfoot. In the flat heel lift study, however, the midfoot contact area was considerably reduced by heel lifts [5]. This is partially because a heel lift rotates the foot onto metatarsophalangeal joints, lifting both the midfoot and rearfoot away from the ground. Moreover, the midfoot and rearfoot are not a rigid combination. The midfoot could be raised further due to the windlass mechanism of plantar aponeurosis in such a foot alignment. Thus the flat heel lift, which is a wedged heel lift with constant rake, may poorly support the midfoot. Insoles based on barefoot plantar contour may also provide inadequate support to the midfoot due to the different midfoot alignment when the heel is lifted. The optimized heel lift in this study was also based on the foot plantar contour however elevating the heel might mitigate the problem.

Previous studies suggested that heel lifts could put the forefoot at risk because of the higher peak pressure under the forefoot, which may have direct relevance to some pathologies [4]. Interestingly, compared to the shoe only condition, the forefoot peak pressure almost remained the same with the optimized heel lift in this study. This could be explained by the fact that the arch support shared part of the load. Whilst the heel peak pressure relief provided by heel lift is consistent across the literature, the magnitude of peak heel pressure reduction percentage by the optimized heel lift is greater than that reported in other studies of flat heel lifts [4, 5, 22]. Apart from the load transfer effect of an arch support, this may also be due to the contoured heel design, which can redistribute the pressure over the entire plantar heel and transfer some pressure from the central part to the peripheral part of the heel. The contoured heel part also helps to maintain the soft tissue of the heel pad, which can absorb impact on the heel [23].

A comparable heel peak pressure reduction was observed with the use of a prefabricated foot orthosis, which was also characterized by a contoured arch and heel [22]. But this foot orthosis also increased midfoot peak pressure by 11%. While in our study, compared to the shoe only condition, the midfoot peak pressure was the same with or without the heel lift. This difference may be explained by the different structure of the arch support between the two inserts. The arch support of the prefabricated heel lift may fully support the arch, so when the arch flattens during locomotion, this arch support would in turn exert load on the arch, increasing midfoot peak pressure. High pressure under the midfoot should also be avoided since the medial arch is not well adapted for weight bearing. The arch support in this study only fully supported the lateral longitudinal arch and there was some space between the arch support and medial longitudinal arch in static foot position to allow the drop movement of the medial longitudinal arch during locomotion.

The midfoot force-time integral remained the same in both test conditions, indicating that the arch support used in this study did not put additional load on the midfoot region. Force-time integral under the forefoot decreased with the use of the optimized heel lift, while force-time integral under the hallux increased. A heel lift puts the foot in a more plantar flexion position, which would constrain the articulation of the bones of the foot, stiffening the foot [24]. A more rigid arch can transfer the load from the rearfoot to the toes more effectively in the toe-off phase. Thus, the increased force-time integral under the toe area may be the consequence of a more rigid foot caused by heel lift.

Due to the decreased foot sensory perception and the elevated the center of mass caused by a thick heel lift [25], the demand of stability control is increased compared to the shoe only condition. Control of the heel motion is important during forefoot contact phase as the heel rocker acts during this part of the stance phase according to the rocker action theory [26]. In this study, a contoured heel surface was designed to support this heel motion. During foot flat phase, the load transfers from the heel to the forefoot. Forefoot and rearfoot are linked by the midfoot, and when the midfoot is suspended, it's less stable for the foot. So the midfoot plays an important role in the balance control during this load transferring phase. Therefore an arch support designed specifically for heel lifts was adopted to improve stability.

The results showed that medial-lateral COP range and velocity during forefoot contact phase and foot flat phase as measures for stability control [5], were not different between the two conditions. This suggests that the optimized heel lift did not have an effect on balance control during forefoot contact phase and foot flat phase. While the previous study showed that flat heel lift reduced the medial-lateral balance control [5] and that seems to be counteracted by the arch support. Arch support has also been proven to be effective to improve balance control in older adults [27], and was used in motion control shoes to control over-pronation [17].

While the optimized heel lift improved the plantar pressure distribution and had no effect on medial-lateral stability, there are still some limitations in this study. The arch support was designed to maintain the midfoot function, however, only plantar pressure data and COP were measured to assess foot function. Kinematic data was not recorded, so the effects of the optimized heel lift on joint angles and moments is unknown. Although the optimized heel lift did not change the force-time integral under the midfoot, whether the newly designed arch support affects the normal movement of medial longitudinal arch is still unknown.

In conclusion, the optimized heel lift improved the biomechanical performance in aspects of plantar pressure distribution. It decreased the heel peak pressure with no additional load on the midfoot and forefoot. The newly designed arch support plays an important role in improving the heel lift performance. The arch support design method in this study may have implications for insole and shoe last design.

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Figure 1. Mean contact area (CA) under three foot regions with and without the optimized heel lift (Error bars: ± SD, * Significant difference, $p < 0.05$)

Figure 2. Mean peak pressure (PP) under three foot regions with and without the optimized heel lift (Error bars: ± SD, * Significant difference, $p < 0.05$)

Figure 3. Percentage of Force time integral (FTI) under five foot regions with and without the optimized heel lift (Error bars: ± SD, * Significant difference, $p < 0.05$)

Figure 4. The range of medial-lateral center of pressure (ML-COP) during FFCP and FFP with and without the optimized heel lift (Error bars: ± SD, FFCP: forefoot contact phase, FFP: foot flat phase)

Figure 5. The velocity of medial-lateral center of pressure (ML-COP) during FFCP and FFP with and without the optimized heel lift (Error bars: ± SD, FFCP: forefoot contact phase, FFP: foot flat phase)

Fig 1

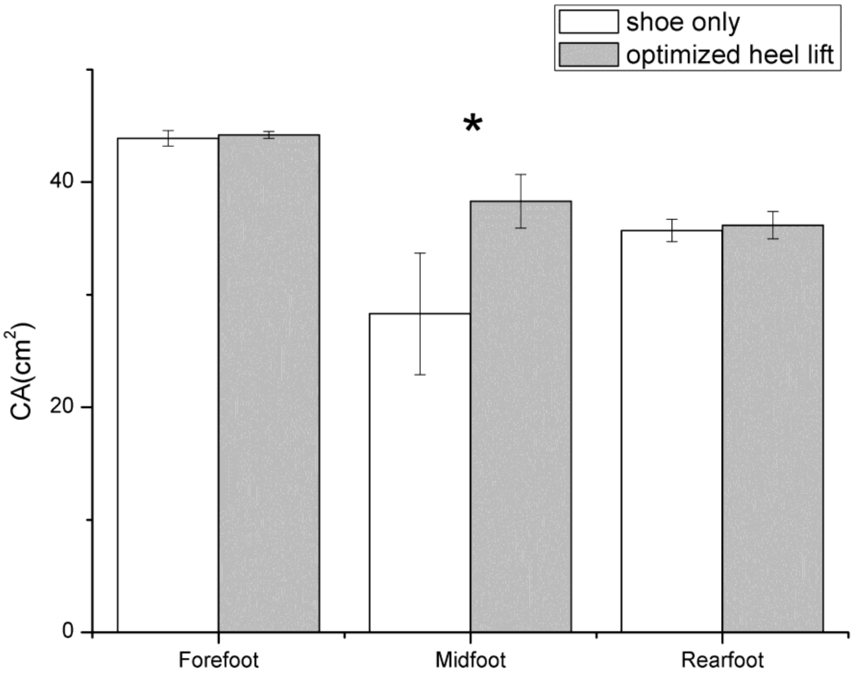

shoe only
optimized heel lift
*
40
20
0
CA(cm2)
Forefoot
Midfoot
Rearfoot

Fig 2

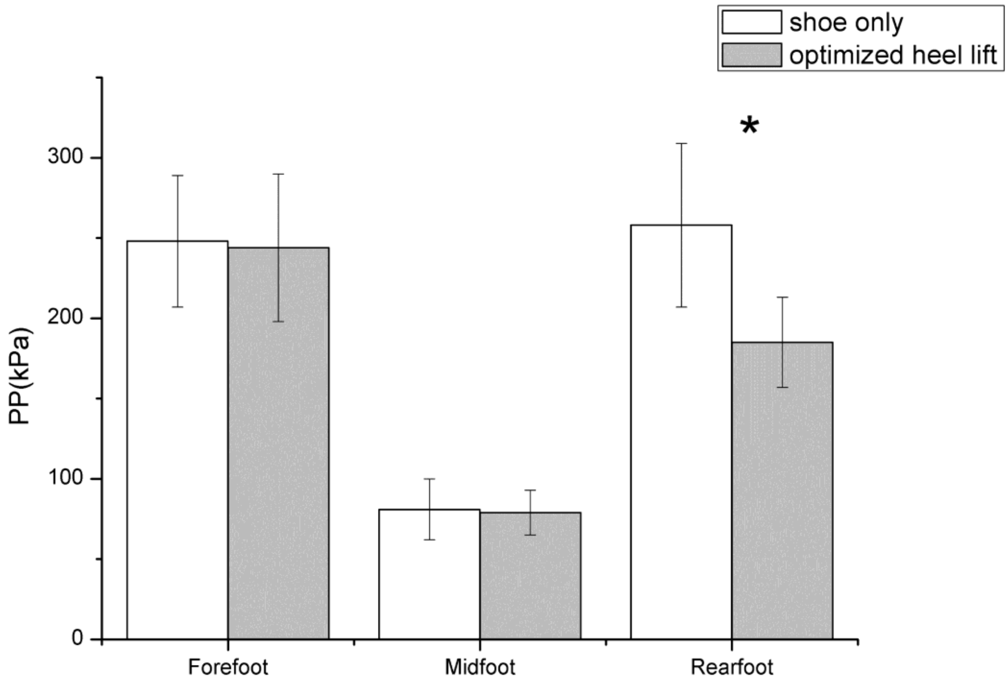
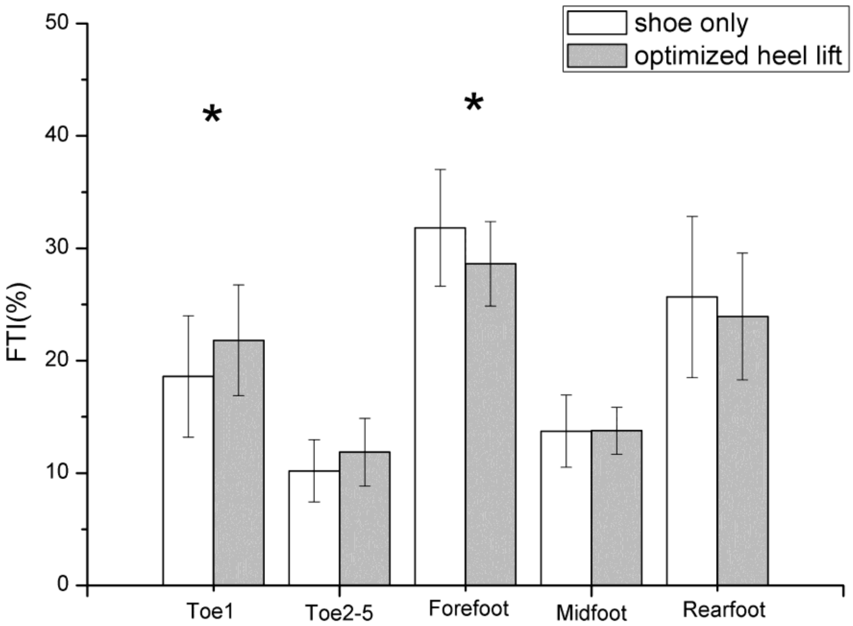

shoe only
optimized heel lift
*
300
200
100
0
PP(kPa)
Forefoot
Midfoot
Rearfoot

Fig 3



shoe only
optimized heel lift
FTI(%)
50
40
30
20
10
0
*
*
Toe1
Toe2-5
Forefoot
Midfoot
Rearfoot

Fig 4

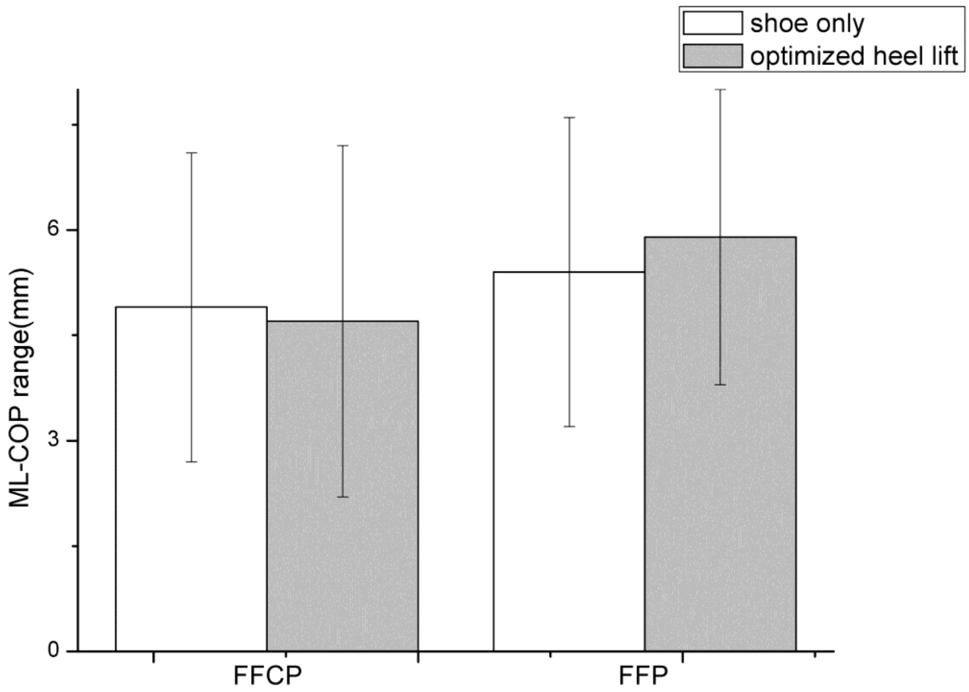
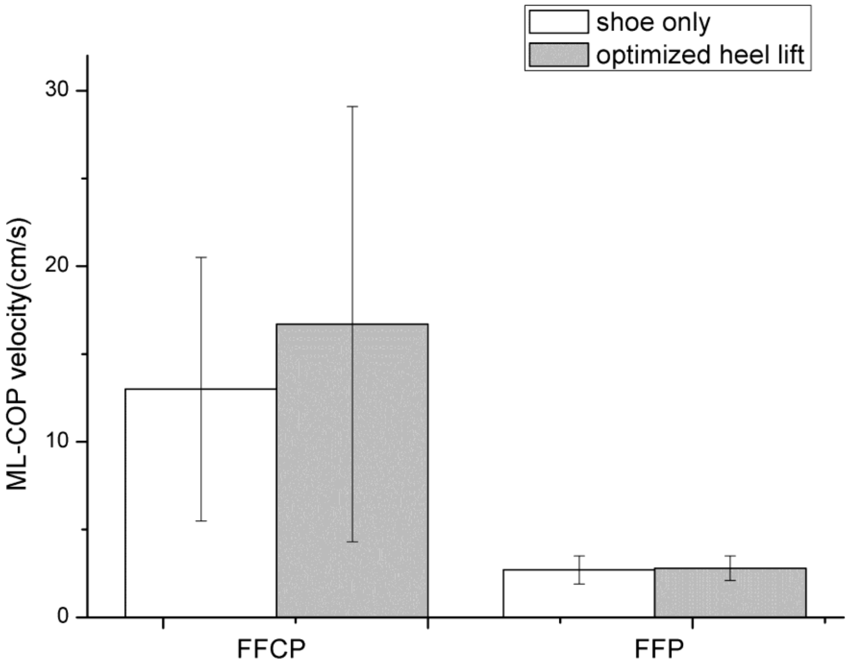


Fig 5


shoe only
optimized heel lift
ML-COP velocity(cm/s)
0
10
20
30
FFCP
FFP